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Dedicated Robotic Servicing for the Space Station

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is presented.

1. ABSTRACT

This paper presents the concept of a series of dedicated robotics manipulators that would be resident in the subsystems of the Space Station. These would be used to do Orbital Replacement Unit (ORU) exchanges, inspection of the components, and in certain cases subsystem assembly. By performing these well defined tasks automatically, higher crew productivity would be achieved. In order to utilize the robots effectively ORU's must be designed to allow remote release and quick disconnection of the electrical, fluid, and thermal connections. The robot must be of a modular design for ease of maintenance and must have an adaptive control capability to make-up for slight errors in programming.

2. INTRODUCTION

The construction, operation and maintenance of the Space Station will present many challenges. In the past space based systems required that the components be certified for the life of the mission with little or no opportunity for servicing. Since the Space Station will be a permanent manned platform in space the opportunity exists to not only service and maintain the components but also to update them as improved technology is developed. With this in mind it is important to utilize available resources and techniques to design the station to be as easily assembled, serviced, and maintained as possible. In addition it is important to keep in mind that the purpose of the astronauts presence on the space station is to provide support for the experiments and manufacturing efforts in space and not to be incumbered with the mundane tasks of station maintenance and servicing.

3. METHODS FOR ASSEMBLY, SERVICING, OPERATION, AND MAINTENANCE

Three methods exist for assembly, servicing and maintenance of the Space Station. These are Extra-Vehicular-Activity (EVA), Inter-vehicular Activity (IVA) using remote teleoperated manipulators and automation in the form of fully automatic robotic manipulators.

EVA

EVA provides the greatest flexibility of the three methods since the astronaut can interact directly with the system. However, this presents the highest risk to the astronaut. In addition several other drawbacks exist. This method is expensive in that the life support systems (EVA suit) are expensive to maintain with costs estimated to be \$80,000 per EVA hour. Also when comparing the time to perform tasks during EVA to normal activities on the ground it can take up to eight times as long to perform the same task. Additional time must be spent in pre and post EVA activities. With these facts in mind it would thus be important for the astronaut to remain in the station unless absolutely required to leave.

IVA

IVA allows the astronaut to remain in the station and perform tasks outside using a remote teleoperated manipulator. Presently two systems the Flight Telerobotic Servicer (FTS) and the Mobile Service Center (MSC) have been identified to do this. Teleoperation allows a high degree of flexibility in positioning the manipulator to perform the tasks since it is under continuous control of the astronaut. However, it is not a simple task to position the manipulator even using multiple cameras and displays. This method is also time consuming and can take up to sixteen times as long normal ground activities. In addition the astronauts

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attention is required even for the simplest activities such as moving along the truss. Also the manipulator is making unplanned moves that can impart inertial loads on the station resulting in vibrations or effecting the validity of low g experiments.

ROBOTICS

The last method is to use fully automated devices such as robots. Robotic devices can be preprogrammed to perform tasks that would not require the direct attention of the astronaut. As part of the program the robot could pause at critical points and allow the astronaut to view the operation and correct the motions, if necessary, before continuing. The ability to control the robot remotely would be provided as a back-up. Because of the relative inflexibility of the robotic devices the tasks would have to be well defined. These tasks would include ORU removal and replacement, component inspection, and, in limited cases, assembly. This would free up the astronaut to do other less defined tasks such as shuttle unloading and satellite capture and servicing using the teleoperated devices. It would be difficult to program a single mobile robot to service all parts of the station. A more viable solution would be to provide dedicated robotic devices as an integral part of the Space Station subsystems.

4. DEDICATED ROBOTICS

This concept provides for modular robotic devices that would be dedicated to the assembly, operation and servicing of particular subsystems on the Space Station. By limiting the tasks required of a particular robot to those for that subsystem the complexity can be significantly reduced.

ORU REPLACEMENT

The primary task of the dedicated robots would consist of removal and replacement of ORUs. The replacement would be performed on a preprogrammed basis and would not require intervention by the astronaut. Because the robot is local to the subsystem, it could aid in the diagnosis of the failure through subsystem testing. If the immediate cause of the failure cannot be identified, or narrowed to a particular ORU the robot would be available to do ORU swapping to determine which component had failed.

ASSEMBLY

Well defined assembly tasks such as first time insertion of ORU's into the subsystems could be accomplished using the robots. With proper considerations given component design such as a common interface and methods of locking the component into place on the structure the robot could perform more complicated assembly operations. These same techniques would be useful in reducing the complexity and time required to do assembly using EVA or IVA. Using multiple robots in the individual subsystems would allow simultaneous operations to proceed.

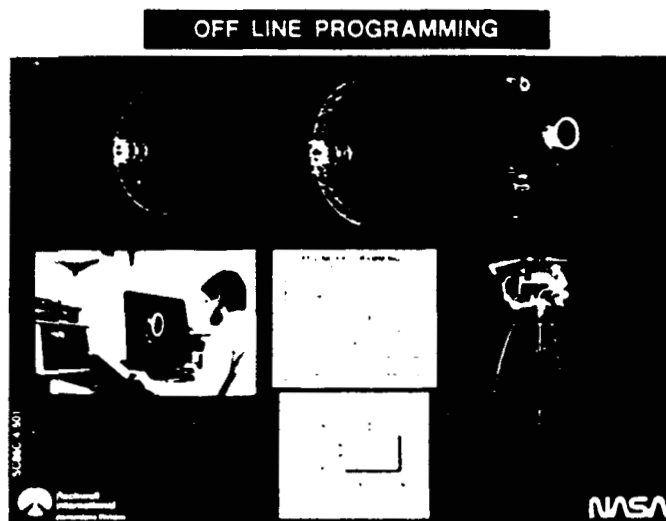
INSPECTION

If it is determined that the cause of the failure is external to the ORU, the astronaut could use the robots sensors and vision system to help identify the cause of the failure. The astronaut would either program the robot to make the repair or use the information obtained to help plan an EVA. Preventative inspections and service of the components in the subsystem would help to predict and prevent catastrophic failures. These could be carried out on a regular basis without astronaut attention and be reported directly to the health monitoring system.

PROGRAMMING

A primary concern for use of robots would be the programming of the many and various tasks. This could be accomplished using graphic simulation and Offline Programming (OLP) based on a CAD data base of the Space Station. The majority of tasks can be identified, programmed, and simulated prior to launch. These programs would be stored and executed as required during operation. However, many tasks would require programming during flight. This could be accomplished by ground crews using the OLP and simulation stations, and then uploaded to the station for execution. The astronaut could perform the simulation (and programming if necessary) on board the Space Station to verify that the task will be accomplished to his/her satisfaction. The OLP/simulation system would be provided with a user friendly interface. Specifying the particular subsystem in question would bring a simulated cell onto the display with the robot and all components. By simply indicating the positions to move to or the task to perform the program would be simulated and down loaded to the robot for execution. A similar system to this is being developed at Rocketdyne for welding the Space Shuttle Main Engines as shown in figure 1.

FIGURE 1

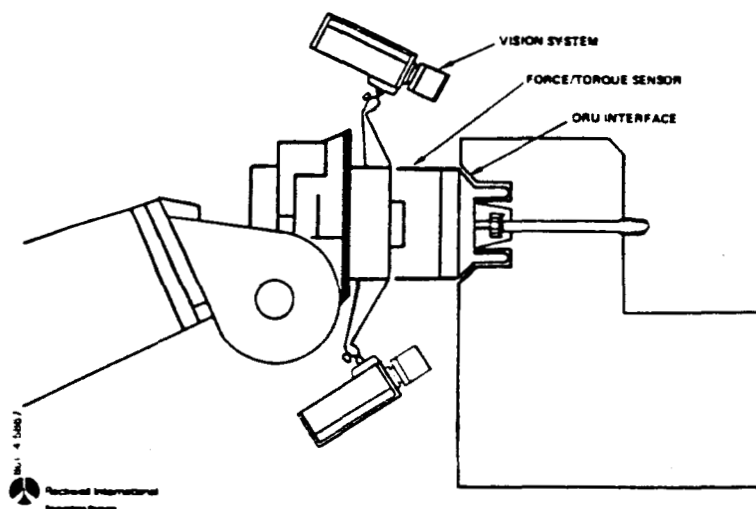


END EFFECTORS

Critical to the operation of the robot, or any remote manipulator would be the ability to interface with the various ORUs. The end effector would be designed to mate with the ORU as shown in figure 2 and include a mechanism for actuating the built in locking and ejection system. This will require the ability to easily change end effectors to accommodate various ORUs within the subsystem. In addition a compact end effector which houses multiple sensors could be provided. This would be used during the regular inspection periods and for trouble shooting and diagnosing problems.

FIGURE 2

TASK SPECIFIC END-EFFECTORS REMOVE AND REPLACE ORU'S



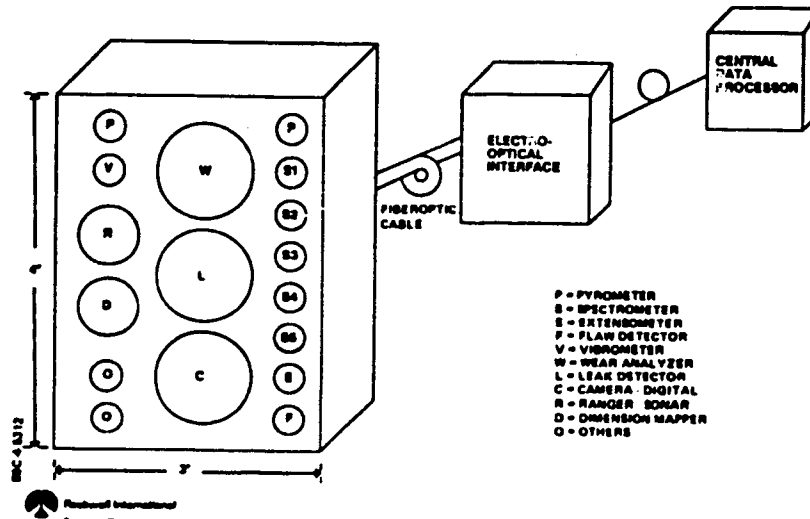
SENSORS

Offline programming and graphic simulation provides a path for the robot which will avoid collisions. To make up for the variation between the programmed path and the actual path both vision and tactile sensors will be required. The vision system as shown in figure 2 will allow the robot to adapt to variation in the location of the ORU interface and position the

robot for final docking with the ORU. Additionally the system would include an optical character reader to identify the ORU. A force/torque sensor in the wrist would be used to adaptively position the robot to prevent jamming and provide a smooth, parallel insertion. This is also shown in figure 2. During the inspection task, various types of sensors will be required. Voltage, current, logic, and communication checks can be performed with a "plug in" type connection to ports on the ORUs. Measurement of mechanical properties such as vibration, temperature, wear, torque and surface defects are more difficult. Figure 3 shows a concept for a compact end effector with multiple sensors that are fiberoptically coupled to the control electronics.

FIGURE 3

END EFFECTOR FOR COMPREHENSIVE INSPECTION BY DEDICATED SERVICING ROBOTS

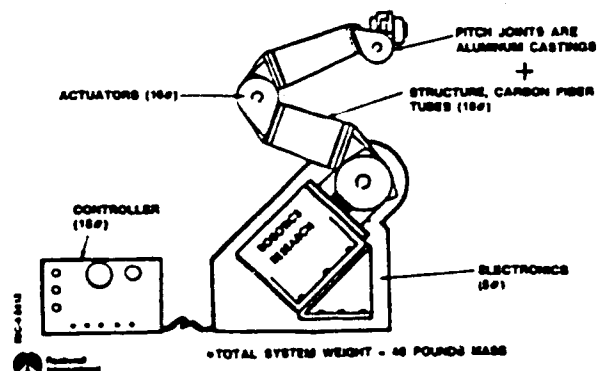


5. ROBOT DESIGN CONSIDERATIONS

By limiting the envelop to a particular subsystem on the station the robot manipulator can be designed as a rigid structure thus simplifying the control. A modular design would allow similar components to be arranged in different configurations to accommodate the variations in the tasks. Due to the lack of gravity the robot need only provide the force necessary to accelerate and decelerate the ORU. By programming very low accelerations and decelerations the axis motors and drives can be made small and compact. This would have the additional advantage of reducing the inertial reaction on the Space Station structure. The use of composites in the design of the manipulator links can provide a light weight and rigid manipulator which is capable of moving large masses. Also use of direct drive motors would reduce the weight. Figure 4 shows the design of redundant 7 axis robot with a 90 inch modular arm whose total weight with control is estimated to be 46 lbs.

FIGURE 4

ROBOTIC SYSTEM WEIGHTS



6. ADVANTAGES TO DEDICATED ROBOTS

There are several advantages to the use of dedicated robotics over other methods discussed. Present plans call for the use of two teleoperated devices, the Mobile Service Center (MSC) and the Flight Telerobotic Servicer (FTS), to perform all remote assembly, service, and maintenance tasks on the Space Station. This would create a problem if more than two tasks were required at the same time especially if the tasks were on opposite ends of the station. Dedicated robots could perform simultaneous tasks on various parts of the station in many cases without requiring the direct attention of the astronaut.

REDUCED ORU COUNT

Many critical systems on the Space Station will require double, triple or quadruple redundancy. By utilizing dedicated robots failed components can be replaced immediately rather than waiting for a planned service interval. This would alleviate the need to provide as high a redundancy level as predicted and thus reduce the ORU count and number of spares required.

PREVENTATIVE MAINTENANCE

By providing the local ability to do inspections and subsystems checks with the robot, it will be easier to determine the cause of the failure and to identify the failed component. Also by performing regular inspections with the robot, failures can be predicted and corrective action taken before a catastrophic failure occurs which could damage adjacent components.

DESIGN FOR SERVICE

As mentioned before, space based systems in the past required that the components be certified for the life of the mission. These former systems in comparison to the Space Station were relatively short lived and less complex. Since the mission life of the Space Station is 30 years, components are required to have a mean time between failure (MTBF) of from 10 to 30 years. In order to obtain these high MTBF's, significant development and manufacturing costs will be incurred. With the use of dedicated robots the ability to maintain and service the Space Station would be significantly enhanced. This would provide the opportunity to design the components for a shorter service life of from 1 to 5 years and thus avoid some of the initial development and fabrication costs associated with commissioning of the Space Station. In addition, as new technology is developed obsolete components could be easily replaced so that the Space Station remained at the highest state of the art obtainable.

7. REQUIREMENTS FOR USE OF DEDICATED ROBOTS.

In order to utilize robots consideration will have to be given to the design of the Space Station and its subsystems and components. These same considerations will also provide for ease of service and assembly by EVA and IVA.

ORU DESIGN

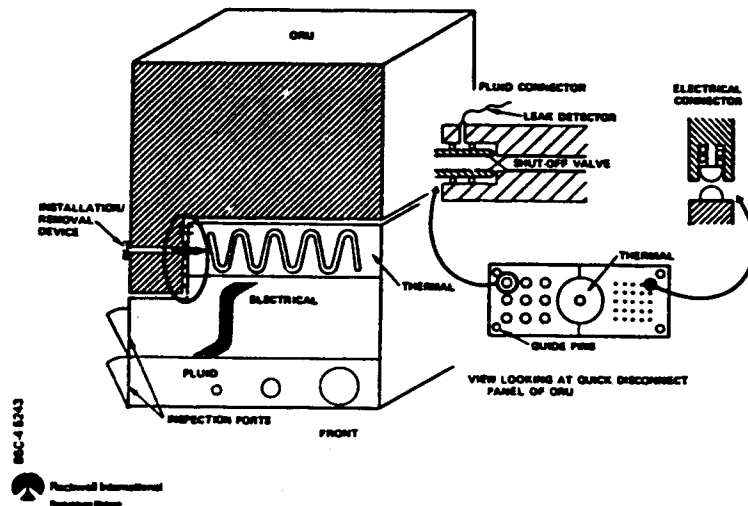
The Orbital Replacement Units should be of a modular design and provide for a common interface between the ORU and the manipulator end effector. A range of interface sizes should be provided to accommodate the different size ORU's. This interface should be designed with adequate lead-in so that a slight misalignment of the end effector would not cause jamming. An alignment target should be provided so that the vision system can locate and do final positioning for connecting to the ORU. In addition identifying markings should be provided adjacent to the target so that they may be verified by the optical character reader.

Quick disconnects should be provided for electrical, communication, fluid and thermal connections to the ORU. Fluid connections should contain a check valve shut off and a leak detection device with double seal arrangement to determine if the check valve has sealed. The robot can be programmed to pause for a leak check. If a seal has not been achieved the removal can be aborted.

A method to connect/lock and to unlock/eject the ORU should be provided so the manipulator is not required to push or pull on the ORU. This will prevent uncontrolled motions by the manipulator when the ORU is removed and provide the forces necessary to overcome the required contact pressures. The actuator for this mechanism would be contained in the end effector of the robot.

Many of the initial start-up and servicing problems on complicated systems such as the Space Station are associated with the connections to the individual components. An additional requirement should be to route the electrical cables, fluid lines and connectors in such a manner that they may be easily inspected and repaired remotely from the front panel. A concept of this ORU design is shown in figure 5.

FIGURE 5
ORU SERVICEABLE CONNECTIONS



CAD DATA BASE

In order to provide for offline programming and graphic simulation of the robot tasks an accurate CAD data base of the Space Station will be required. This will assure that the robot path will not interfere with other portions of the station and that the actual robot motions can be executed. In addition this data base will be invaluable in configuration control and redesign during growth of the Space Station.

DELIVERY OF ORUS

Replacement ORU's, components, and end effectors must be delivered from storage to the individual robot system. Failed components and unused end effectors must be returned for storage or repair or delivery to earth. In order to accomplish this an Automated Guided Vehicle (AGV) system would be provided as shown in figure 6. This system would consist of battery operated carts that would be guided by a rail attached to the station structure. The carts would receive control signals via the rail and be directed to the specific location requiring the replacement part. These carts would be loaded and unloaded by a Automatic Retrieval and Storage (ARAS) system as shown in figure 7. This would assure that the proper components were delivered in a timely manner and would also support simultaneous servicing of the subsystems. The AGV would also be useful in delivering equipment and tools to the teleoperated manipulators and astronauts during EVA.

FIGURE 6
AUTOMATIC GUIDED VEHICLE (AGV)
FOR DELIVERY OF ORUS

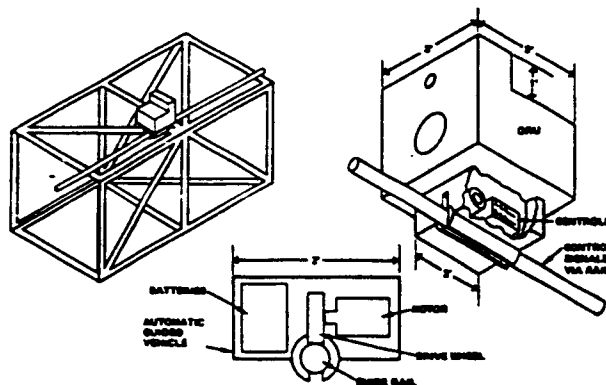
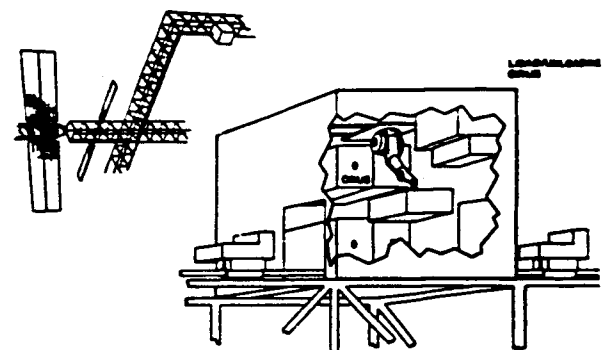
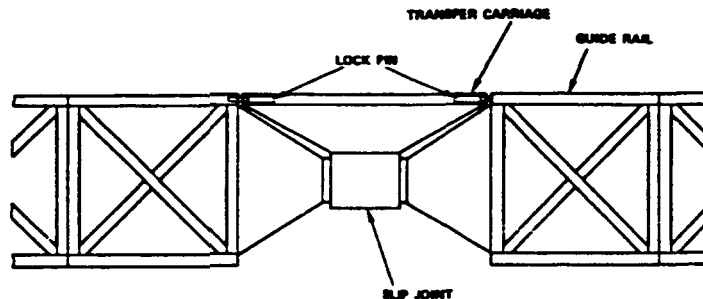


FIGURE 7
AUTOMATIC RETRIEVAL AND
STORAGE SYSTEM FOR ORUS



Crossing the alpha joint will be a major problem in servicing components on the power generation booms. One alternative is to stop the rotation of the alpha joint during the time the remote manipulator or AGV is crossing the joint. This, however, requires additional power to stop and start the joint. To overcome this problem a Transfer Carriage could be provided as shown in figure 8. When the AGV arrives at the alpha joint the carriage would be locked onto the Space Station structure. The AGV would move onto the Transfer Carriage. When the power boom rotates into position the Transfer Carriage would lock onto the power boom and disengage from the structure. The AGV would then move onto the power boom.

FIGURE 8
AUTOMATIC GUIDED VEHICLE (AGV)
TRANSFER CARRIAGE FOR ALPHA JOINT



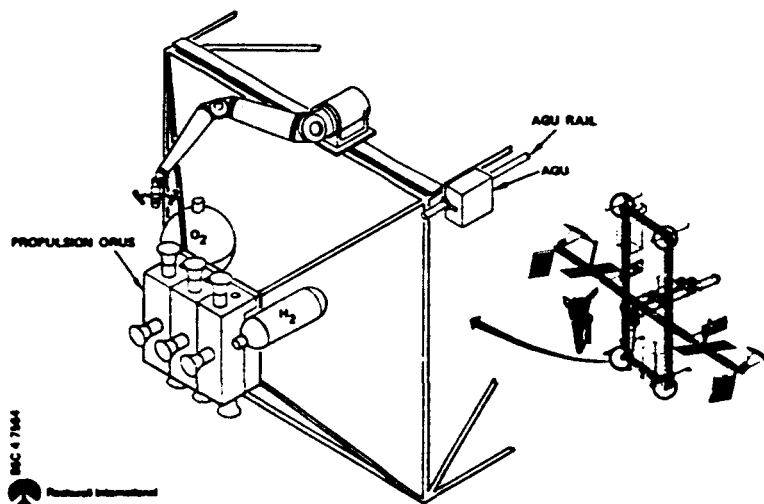
8. POTENTIAL APPLICATIONS

Various subsystems on the Space Station are candidates for dedicated robotics. Two typical applications would be the Laboratory module and the Propulsion unit.

PROPULSION

A typical concept for servicing components on exterior system of the station is shown in figure 9 for the propulsion system. In this case the robot could exchange ORU's consisting of three propulsion units. The robot would also perform regular inspections of the propellant lines and fittings to check for leaks. A modular end effector could also be developed which would fit around a leak in a section of tubing and repair the tube in-situ.

FIGURE 9
PROPULSION SYSTEM SERVICING

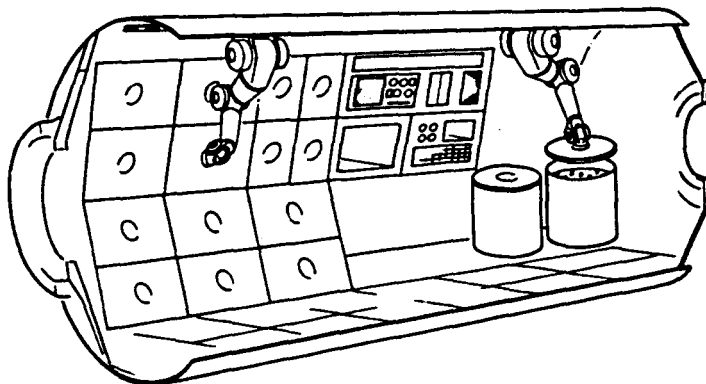


LABORATORY MODULE

As shown in figure 10, several dedicated robots can be provided in the laboratory module for servicing and operation of the experiments. This would reduce the cost to the customers by allowing them to automate their experiments without having to build it into their equipment. Instrumentation could be shared between experiments and customers thus lowering the cost. In addition, customers could be allowed to control their experiments from the ground by using the OLP/simulation facilities. Many experiments will be carried on in a vacuum environment. By servicing these experiments with a robot, the astronaut would not be required to suit-up.

FIGURE 10

DEDICATED ROBOT IN EXPERIMENTAL BAY



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9. CONCLUSIONS

Modern factories today rely on multiple dedicated robotic devices to increase the productivity of their workers and remove them from the repetitive and boring manufacturing tasks. The Space Station can also benefit from applying this technology to servicing and maintenance. In addition with the proper thought to component design the possibility exists that the dedicated robot systems could aid in assembly. This would have the added advantage of allowing the assembly of various subsystems to proceed simultaneously and reduce the time to commission the Space Station. This does not suggest that the Space Station can be totally automated at this stage. There will always be tasks that require the direct intervention of the astronaut. However many well defined and repetitive tasks exist that would benefit from the application of a robot requiring a minimum amount of adaptive control. By applying existing technology as well as limiting their use to well defined tasks dedicated robots could be made available for IOC.

10. ACKNOWLEDGEMENTS

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